Algorithms for Combining Airspace Sectors

Michael Bloem, Pramod Gupta, and Parimal Kopardekar

A heuristic algorithm for combining under-utilized airspace sectors to conserve air traffic control resources is described and analyzed. Simulations and analysis using historical air traffic data and operational sector combination data suggest that systematically combining under-utilized sectors can lead to fewer sectors and therefore a more efficient utilization of resources. Currently, sector combinations are restricted to occur within groups of sectors called areas of specialization. A second heuristic algorithm is proposed that defines new groups of sectors that may be combined. These new groups allow more sector combinations and could be building blocks for new areas of specialization. An analysis of the new groups of sectors suggests that they allow for more frequent sector combinations than existing areas of specialization, and therefore even further efficiencies. Feedback from managers at the Cleveland Air Route Traffic Control Center suggests that both of these algorithms would be useful in Center operations.

INTRODUCTION

Dynamic Airspace Configuration (DAC) involves dynamically changing how the national airspace is divided into Centers, sectors, or other airspace components to increase user and service provider efficiency. Recent DAC research has produced numerous concepts and tools that achieve goals such as balancing controller workload between sectors and building sectors that conform to desired air traffic flows. This recent research uses theoretical tools such as integer programming [Yousefi and Donahue, 2004], computational geometry

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Received January 16, 2009; accepted May 1, 2009.

Air Traffic Control Quarterly, Vol. 17(3) 245–268 (2009) CCC 1064-3818/95/030163-20

[Basu et al., 2008], and genetic algorithms [Delahaye et al., 1994; Xue, 2008]. While the research shows promise, two weaknesses have surfaced. First, much of this previous research does not explicitly minimize the number of sectors, and therefore the resources required to manage a traffic situation. Second, many of these approaches envision that new sectorizations will be implemented at least seasonally and up to multiple times each day. The air traffic control system is not able to implement new sectorizations with this frequency, nor will it be able to in the near term. In this article, near term is defined as within five years. Currently, implementing changes in sectors takes 6-18 months, even though most changes in sectors are only incremental. Training a controller on a new set of sectors requires six months to two years. Increasing the frequency with which new sectorizations can be implemented will require significant improvements in automation. Therefore, many approaches suggested in DAC research cannot be implemented in the near-term.

In this article, an algorithm for systematically combining underutilized existing sectors is presented and analyzed. The suggested algorithm directly fills the two gaps in DAC research mentioned above. First, the explicit objective of this algorithm is to reduce the number of sectors and therefore the quantity of air traffic control (ATC) resources required to control a given quantity of air traffic in a Center. This may lead to a more flexible and efficient utilization of the controller workforce. Second, this algorithm can be implemented to support operational decisions. Airspace sectors are already combined every day. Moreover, the algorithm uses measures of sector capacity and predicted sector utilization that are readily available in air traffic control Centers. These two gaps are further filled by a second algorithm that defines groups of existing sectors that would be permitted to combine. These groups could be appropriately merged into controller areas of specialization by subject matter experts who would also consider other factors relevant to defining areas of specialization. Areas of specialization can be redefined over 1-2 years, so the new areas of specialization could be implemented in the near-term. Moreover, this algorithm defines groups of sectors that may combine with the objective of creating opportunities for more sector combinations, thereby leading to a more efficient utilization of ATC resources.

In the next section, the algorithm for combining existing airspace sectors is described, and its qualitative strengths and weaknesses are discussed. This section is followed by a description of an algorithm for defining groups of sectors that are permitted to combine. The “Quantitative Analysis of the Algorithms” section contains simulations and analyses demonstrating that these algorithms lead to a further 9-27% reduction in the resources required to manage a

Center's airspace over the reduction achieved by current operations. Subject matter expert feedback is positive but also suggested some additional issues to consider. This feedback is discussed in the "Subject Matter Expert" section. The article finishes with a "Future Research" section and some concluding remarks in the "Conclusion" section.

ALGORITHM FOR COMBINING AIRSPACE SECTORS

Algorithm Objective: Reduce Sector Hours

The number of sector hours is calculated by multiplying the number of sectors operating at each time interval by the length of the time interval and then summing over all time intervals in a time period of interest. The algorithms presented in this paper attempt to reduce the sector hours required to manage a piece of airspace for a period of time.

A more obvious objective might be to reduce controller hours: the number of controllers required to manage some airspace during a time interval, multiplied by the duration of the time interval, and summed over all time intervals in a time period of interest. Sector hours is a different metric from controller hours. Depending on how busy a sector is, one or two controllers (or very rarely three controllers) will manage the traffic in a sector. Therefore, fewer sector hours may or may not correspond to fewer controller hours. However, reducing sector hours is still assumed to be an appropriate objective and it is used instead of controller hours in part because it is easier to compute. Sector hours is also used because when fewer sector hours are required to operate a piece of airspace without sectors exceeding their capacities, two things may happen, and both of them are desirable. The first is that fewer controller hours will be required, thereby increasing staff flexibility and efficiency. The second is that more sectors will be relatively busy and will have two controllers working on them. This can be beneficial because two controllers working a busy sector may be more engaged and efficient than two controllers each working alone on relatively empty sectors, assuming that the combined sector is not overloaded.

Sector Utilization and Capacity Metrics

The algorithm presented in this article for combining sectors is based upon a measure of predicted excess capacity in sectors. The most simple and widely used sector utilization metric is the maximum instantaneous aircraft count during a 15-minute time interval.

Also, each sector has a *Monitor Alert Parameter* (MAP) value that designates the sector's capacity in units of instantaneous aircraft count. For this study the maximum instantaneous aircraft count will be used to measure the utilization of a sector and the MAP value will be used as its capacity.

Using maximum instantaneous aircraft count as the measure of utilization has several advantages. It is simple and widely used in Federal Aviation Administration (FAA) Air Route Traffic Control Centers (ARTCCs). The Enhanced Traffic Management Tool (ETMS) predicts this count in real time for planning purposes, and the uncertainty in its prediction is relatively well understood [Wanke et al., 2003; Wanke et al., 2005]. In many cases this measure does not correlate well with the actual workload in a sector as indicated by air traffic controller feedback. Therefore, more sophisticated and accurate measures of complexity have been developed [Kopardekar et al., 2007]. However, these measures are not readily available nor predicted in real time, so they were not considered.

A mechanism for determining the capacity of a new sector that is the combination of two smaller sectors must be established. Many common sector combinations have predetermined MAP values. Another possibility is to apply the method used by the FAA to determine MAP values for each sector [Federal Aviation Administration, 2006]. This method sets MAP values as a function of average dwell time of aircraft in the sector. Airspace capacities can be set based on the volume of the newly created airspace sectors and a model of controller workload [Welch et al., 2007]. A more conservative and straightforward approach used in this article is to simply compare the two MAP values of the sectors being combined and to set the capacity of the new combined sector to the larger MAP value. Future work may consider a more realistic and less conservative determination of the capacity of a combined sector.

Algorithm Parameters

The algorithm uses three parameters, which are summarized in Table 1. Altering these parameters will change the algorithm sector combination results. Also, altering these parameters allows a user to configure the algorithm to fit with some of the operational procedures of the air traffic control service provider.

The first parameter, t_c, is a vector that contains the times at which sectors may combine or split apart. An air traffic control service provider may wish only to combine sectors during times of the day that are not busy or when a shift change of air traffic controllers is scheduled to occur. Frequent sector combining and splitting may lead to better capacity management and utilization, but there are

Table 1. Algorithm Parameters

Parameter	Name
t_c	Combination time vector
t_n	Advance notice duration
g	Minimum capacity gap

also costs associated with combining and splitting sectors (see the "Operations for Combining and Splitting Sectors" section).

With this algorithm, sector combinations may be scheduled at any length of time before they are implemented. This allows the air traffic control service provider time to schedule employees or otherwise prepare for the combination. The advance notice duration parameter, t_n, is the time between sector combination planning and execution. Larger values for this parameter require sector combinations to be based on longer term, and thus less accurate predictions of sector utilization.

Finally, the parameter g is the minimum capacity gap parameter. When evaluating whether neighboring sectors can be safely combined, the predicted excess capacity of the hypothetical combined sector must be greater than g. When changing this parameter, the user will trade off between increased efficiency and increased likelihood that a combined sector will exceed its capacity and need to be split. This parameter is typically set as an absolute number, but it can also be set as a percentage of the combined sector's MAP value.

A parametric study that investigates the impact of changing the value of g, expressed as a percentage of the combined sector's MAP, is presented later in the article. A more complete parametric study can be found in the paper where this algorithm for combining sectors was introduced [Bloem and Kopardekar, 2008].

Permissible Sector Combinations

There are two versions of this algorithm: *restricted* and *unrestricted*. In the restricted version, sectors may only combine with neighboring sectors in the same controller area of specialization. In the unrestricted version, any two neighboring sectors within the same Center can combine, regardless of area of specialization. Presently, all controllers are qualified to work each sector in an area of specialization, but controllers rarely are trained on sectors spanning multiple areas of specialization. Therefore, a near-term implementation of this algorithm should consider that neighboring sectors could only be combined if they are in the same area of specialization.

In the mid term, it is expected that generic airspace sectors will enable larger areas of specialization. The idea behind generic airspace sectors is that by displaying sector information to controllers and by providing controllers with automation such as automated conflict detection and resolution, controllers will be able and allowed to control a relatively large number of different sectors. As more sectors may be combined, it will be more difficult for area supervisors to determine an appropriate set of sector combinations, making an algorithm that suggests a good set of sector combinations more useful. The unrestricted version of the algorithm is meant to evaluate the performance of the algorithm when generic sectors have removed the need for areas of specialization within Centers.

Sectors are easier for controllers to understand when they have uniform lower and upper altitudes. However, when sectors are combined, the resulting combined sectors may contain altitude "steps". An altitude step is a discontinuity in the altitude of the upper or lower boundary of a sector. Altitude steps make sectors hard to visualize when they are viewed on a two-dimensional scope such as those currently used by controllers, so no more than one step is permitted per combined sector.

Although not a strict requirement, low-altitude sectors are rarely combined with high-altitude sectors. This is because traffic characteristics are different in low and high altitude sectors, so controlling both types of traffic at the same time is generally difficult. Therefore, any area of specialization that contains both low and high sectors is actually made up of two groups of sectors that may combine. For this research, low sectors were allowed to combine with high sectors only in the rare cases in which a high sector is exactly the same shape of a low sector and is directly above it (the definition of a neighboring sector is described in the next section).

Algorithm for Combining Airspace Sectors

A block diagram depicting the algorithm for combining sectors is shown in Figure 1.

There are two inputs to the algorithm: 1) predicted sector utilizations and 2) a description of the uncombined sectors. Sector utilization can be predicted in many ways; ETMS sector utilization predictions are in the correct format and are readily available, so they could be used. The utilization of sectors is expressed as the maximum instantaneous aircraft count for each 15-minute time interval in the period of time that this set of sectors will operate (defined by the time between the relevant entries of the t_c vector). The other input is the information about uncombined sectors. The capacity, area of specialization, and neighbors of each sector must also be known. In this work the MAP value is used as the capacity. For this research, a sector's vertical neighbors are only those sectors that share its entire boundary and are directly above or below it.

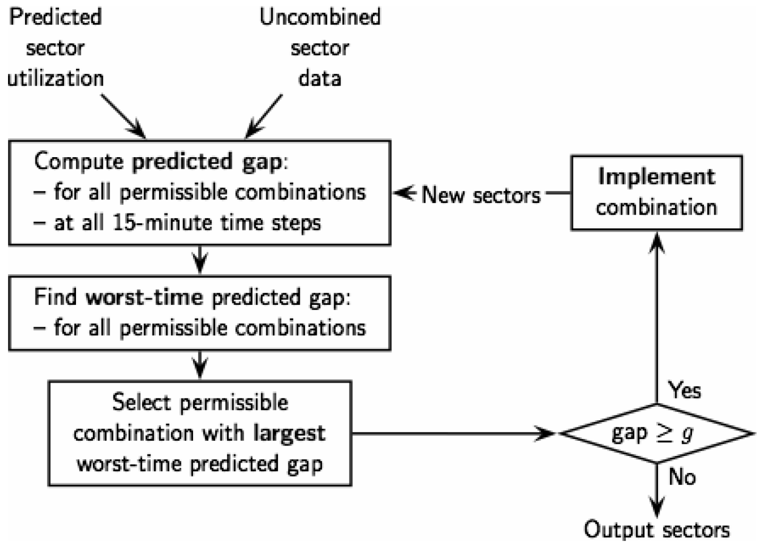

Figure 1. Algorithm for combining sectors.

A sector's horizontal neighbors are any sectors with which it shares a horizontal boundary and some altitude level.

There are four main steps in the proposed algorithm:

1. Compute the predicted capacity gaps for all permissible two-sector combinations in the center and at all 15-minute time steps under consideration.
2. Find the smallest predicted gap among all of the 15-minute time steps under consideration for each of the permissible combinations. This is the worst-time predicted gap.
3. Combine the two sectors whose combination has the largest worst-time predicted capacity gap.
4. Repeat until the largest worst-time predicted capacity gap is smaller than the minimum capacity gap.

The first step in the algorithm is to compute the predicted capacity gap for all permissible combinations and at all 15-minute time steps. When evaluating a sector combination, the capacity is the larger of the two capacities, the utilization is the sum of the maximum instantaneous aircraft counts, and the gap is the difference between the two.

The next step in the algorithm is to investigate the capacity gaps for all permissible combinations. The smallest gap that occurs over all 15-minute time steps considered is chosen as the worst-time predicted capacity gap for each combination. The combination with the largest worst-time predicted capacity gap is chosen as the suggested sector combination for this iteration through the algorithm. When multiple combinations have the same worst-time predicted capacity gap, the combination that removes the most flight boundary crossings is chosen. Thus, the algorithm has an implicit secondary objective of building combined sectors that conform to traffic flows by reducing boundary crossings. If this combination has a worst-time predicted capacity gap that is greater than or equal to g, then it is implemented and the resulting new sectors are used in the next iteration of the algorithm. If the worst-time predicted capacity gap is less than g, then the algorithm is done and outputs the final sectors.

The algorithm can be classified as a recursive algorithm. The algorithm can also be classified as greedy because at each step it chooses the best combination: the combination that results in the most excess capacity in the new sectors. This excess capacity can then be used in later steps of the recursion for further sector combinations.

The computational complexity of this algorithm is $O(n^2)$, where n is the number of sectors in the initial sectorization. For the number of sectors in a typical Center, this computation time is not prohibitive. The computational complexity is linear in the duration of each combination time. The complexity grows non-linearly with the number of sector combinations that are implemented, although this number of combinations is not known a priori. In practice, the algorithm executes in a few seconds when calculating hour-long combinations for a center with 50 sectors.

There are several strengths of this algorithm. It reduces the number of sectors without requiring the desired number of sectors to be prespecified. Any building blocks, such as existing sectors, sub-sectors, or new sectors, can be combined by the algorithm. The sector capacity and predicted utilization inputs to the algorithm are available at the Centers, but other measures could be used directly by the algorithm. As discussed earlier, the minimum capacity gap parameter can control the conservatism of the sector combinations. Other parameters enable users to tailor the algorithm to work with some existing operational procedures such as the timing of shift changes.

This algorithm has several weaknesses as well. While using existing sectors as building blocks allows for short-term implementability, it restricts the possible airspace configurations and therefore also restricts the efficiency of the resulting sectorizations. Moreover, while this approach will yield more efficient air traffic control resource utilization, it does not increase capacity where capacity is lacking and will have little impact on air traffic efficiency. From a more technical perspective, a weakness of this algorithm is that it is a heuristic with no guarantee of optimality. Tools from graph theory or integer programming could be used to find a true optimal solution for this problem.

ALGORITHM FOR DEFINING GROUPS OF SECTORS THAT MAY COMBINE

The algorithm for defining groups of sectors that may combine is shown in Figure 2.

This algorithm requires 1) a set of training sector utilization data, 2) sector grouping constraints, and 3) sector data. The sector utilization data contains sector aircraft counts based on historical air traffic data. The set of training data should be representative of the air traffic patterns that will be encountered by the potential groups of sectors that the algorithm will produce.

Another required piece of data is a set of sector grouping constraints. These constraints define sectors that must be in the same groups. This gives the user the ability to ensure that some sectors will be able to combine in the final set of groups defined by the algorithm. For a clean sheet definition of the groups, no such constraints should be specified.

Finally, the algorithm requires sector data. This includes the capacities of the sectors and which sectors are neighbors with which other sectors.

The first step in the algorithm is to compute the sector hours for all permissible combinations of two groups of sectors. This step is shown in the top box in Figure 2. A combination of two groups is permissible as long as the resulting group contains less than or equal to some specified maximum number of sectors per group, s. These permissible new groups are evaluated by implementing them, running the restricted sector combining algorithm with the training

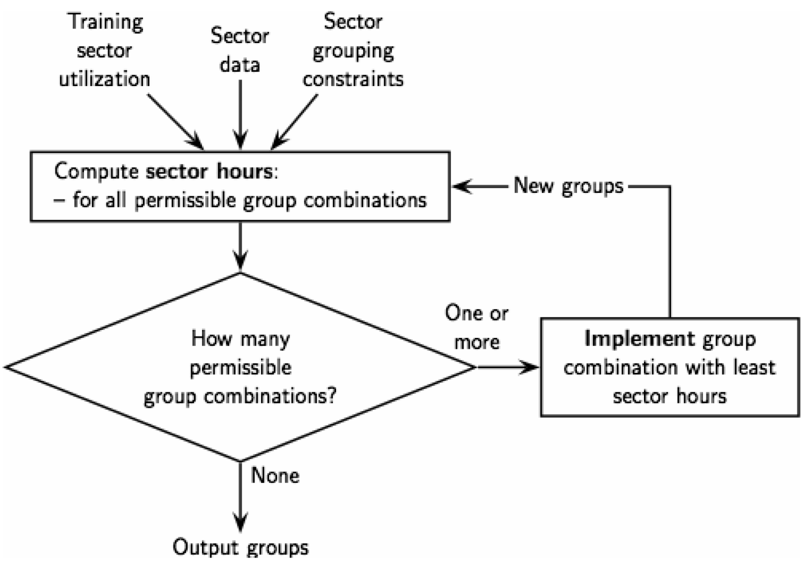

Figure 2. Algorithm for defining groups of sectors that may combine.

data set and with the groups, and computing the number of sector hours that would be required with the set of groups.

The next step is to check if any permissible combinations of groups exist. This step is depicted by the diamond in Figure 2. If permissible combinations of groups do exist, the combination that leads to the least sector hours in the training data set is implemented, and the resulting groups are used as the starting point for the next iteration of the algorithm. The right half of Figure 2 shows this part of the algorithm. Once many groups have combined, the groups contain so many sectors that any combination of groups would contain more sectors than *s*, at which point the algorithm terminates and outputs the group definitions.

There are qualitative strengths and weaknesses to this approach. The constraint input to the algorithm allows the user to prespecify any sectors that must be in the same group of sectors that are permitted to combine. As defined here, the objective is to minimize the number of sector hours. Any metric could be used to evaluate the groups of sectors in the first step of the algorithm. Similarly, any algorithm could be used to compute the number of sector hours that are required by a particular definition of the groups. The number of groups of sectors does not need to be prespecified but is determined by the algorithm, the *s* parameter, and the training data.

As with the algorithm for combining sectors, this algorithm is a recursive greedy algorithm and a heuristic that will not necessarily find an optimal set of groups. Theoretical tools such as constrained clustering, integer programming, or graph theory may be used to find a true optimal set of groups. An additional weakness of this approach is that it is computationally intensive. To find a set of groups for a center with around 50 sectors using a training data set of 5 days requires several days to complete. This is not prohibitive, however, as areas of specialization are redefined over the course of 1-2 years.

QUANTITATIVE ANALYSIS OF THE ALGORITHMS

Simulation Details

Sector aircraft count predictions are a crucial input to the combining sectors algorithm. A realistic sample of sector aircraft count predictions over time is obtained by simulating air traffic in the Future ATM Concepts Evaluation Tool (FACET) [Bilimoria et al., 2001] and counting the aircraft in each sector at each time. The flights scheduled for a day are simulated instead of playing back flight data to eliminate the effect of traffic flow management (TFM) actions on sector aircraft counts. TFM actions, such as miles-in-trail restrictions and ground delay programs, are used to prevent sectors from exceeding their capacities, among other things. Simulating actual traffic schedules allows for an analysis of aircraft sector counts that is unbiased by TFM actions. The flight data input to FACET are Aircraft Situational Display to Industry (ASDI) data. The sectors chosen for these simulations are all low and high (including super-high) sectors containing airspace above 10,000 feet.

Combination times (t_c) occurred each hour, and each combination lasted for an hour. The advance notice duration (t_n) was also set to an hour. Finally, the minimum capacity gap (g) was set to three and the maximum number of sectors per area (s) was set to seven.

Discussion of Results

Metrics. Two metrics are given for the evaluation of the performance of the algorithms. The number of sector hours is the primary metric and is calculated by multiplying the number of sectors operating at each 15-minute time step by the length of the time step and then summing over all time steps.

The second metric is the average over all time steps of the median sector utilization at each time step under consideration. It measures what portion of the deployed air traffic control capacity is utilized.

Comparison of Algorithm for Combining Sectors with Current Operations at Cleveland Center. The performance of the algorithm for combining sectors is evaluated by comparing the sectors it combines with the actual high sector combinations in Cleveland Center. This operational data is from February 5-7, 2008. The algorithm for combining sectors was run on the traffic data from these dates.

The number of sector hours used when no sectors are combined, in current operations, and when sectors are combined according to the restricted and unrestricted algorithm are shown in Table 2. The sector combinations suggested by the unrestricted algorithm lead to fewer sector hours than uncombined sectors or the operational sector combinations. When the restricted algorithm is used, the reduction in sector hours over the operational combinations is still significant but smaller than in the unrestricted case. More sector combinations occur in low sectors than in high sectors because low sectors tend to operate below capacity in Cleveland Center.

Figure 3 shows the average number of high sectors at each hour over time when no sectors are combined, in current operations, and the average number resulting from using the two versions of the combining sectors algorithm. Computing the area under these curves over this interval produces the sector hours results in Table 2. For high altitude sectors, most of the possible combinations are at night, but sector combinations are possible even during busy times of

Table 2. Sector Hours Per Day for High and Low Sectors in Cleveland Center

		High Sectors	Low Sectors
Uncombined	Sector Hours	621	529
Current Operations	Sector Hours	435	Not available
	% Change	−30%	Not available
Restricted Algorithm	Sector Hours	376	256
	% Change	−39%	−52%
Unrestricted Algorithm	Sector Hours	327	189
	% Change	−47%	−64%

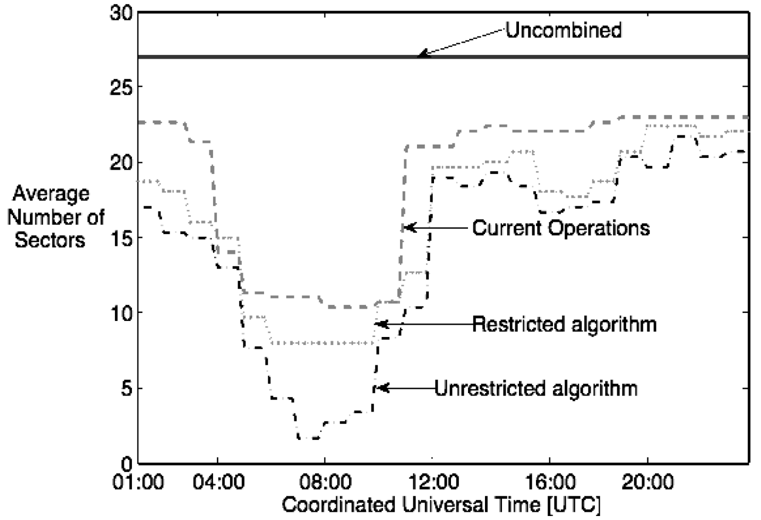

Figure 3. Average number of high and super-high sectors in Cleveland Center.

the day. The unrestricted algorithm is able to reduce the number of operational sectors more than the restricted algorithm or the operational combinations because it is not constrained by areas of specialization. However, the restricted algorithm also is able to reduce the number of sectors more than the operational combinations at almost all times during the day, sometimes by more than five sectors at a time.

Figure 4 shows the same information as Figure 3 for low sectors, except that no current operations data for low sectors were available. Particularly for low sectors, the results suggest that many sectors can be combined at any time of the day.

Algorithm for Combining Sectors Performance in Other Centers. To evaluate the performance of the algorithm in Centers with varying traffic conditions, eleven Centers were analyzed.

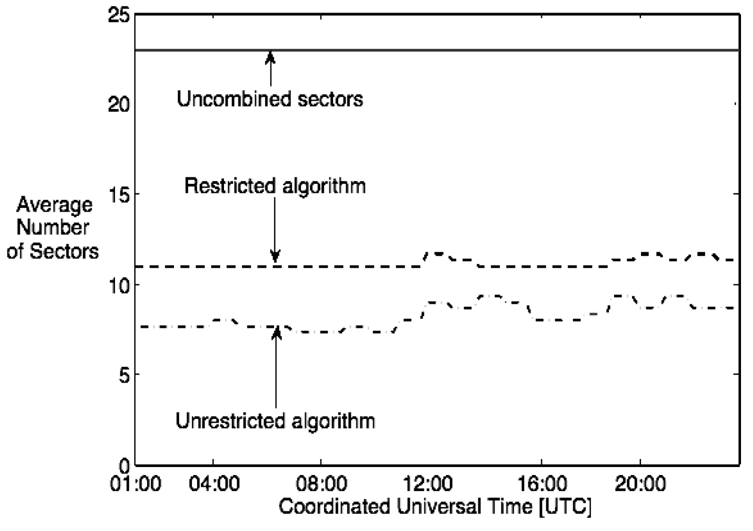

Figure 4. Average number of low sectors in Cleveland Center.

Unfortunately, operational sector combination data were not available for all of these Centers, so the sector combinations could only be compared with uncombined sectors. Furthermore, area of specialization definitions were not known for all of these Centers, so the results here may be based on incorrect assumptions about the areas of specialization. The algorithm was simulated with data from seven good or moderate weather weekdays. Days are classified as good, moderate or bad weather according to the number of hours of weather-related delays in the National Airspace System (NAS). The good or moderate weather days were 2 March 2007, 8 May 2007, 24 May 2007, 29 May 2007, 13 June 2007, 4 July 2007, and 24 July 2007. No analysis was performed with bad weather days in this study as it has been shown previously that the sector-hour results are similar for bad weather days [Bloem and Kopardekar, 2008]. These days are from the busy summer season.

The results are shown in Tables 3 and 4 for the restricted and unrestricted algorithm, respectively. In these tables a negative percentage change in sector hours indicates a reduction of sector hours, and reducing sector hours is the primary objective of these algorithms. It is observed that the reductions in sector hours over uncombined sectors ranges from 20% to 45% when the restricted algorithm is used and from 45% to 60% when the unrestricted algorithm is used. Improving sector utilization is the secondary metric for these algorithms, and they are improving the utilization. The improvement in average median utilization of sectors in the Centers ranges from 30% to 85% for the restricted algorithm and from 80% to 160% when the unrestricted algorithm is used. Cleveland Center is at the higher end of these ranges, which implies that other Centers

Table 3. Average Sector Hours Per Day and Utilization Results for Restricted Algorithm in Various Centers

	Sector Hours			Average Median Utilization		
Center	Uncombined	Combined	Change	Uncombined	Combined	Change
Albuquerque	897	649	−28%	0.1779	0.2583	45%
Atlanta	1035	741	−28%	0.2247	0.3145	40%
Boston	759	562	−26%	0.1419	0.1921	35%
Chicago	1081	707	−35%	0.1925	0.3008	56%
Cleveland	1150	642	−44%	0.1705	0.3127	83%
Fort Worth	920	728	−21%	0.1253	0.1638	31%
Houston	920	645	−30%	0.1714	0.2602	52%
Los Angeles	805	499	−38%	0.1822	0.3296	81%
Miami	736	483	−34%	0.1386	0.2333	68%
Salt Lake City	644	460	−29%	0.1692	0.2441	44%
Washington, DC	1081	882	−18%	0.1359	0.1819	34%

Table 4. Average Sector Hours Per Day and Utilization Results for Unrestricted Algorithm in Various Centers

	Sector Hours			Average Median Utilization		
Center	Uncombined	Combined	Change	Uncombined	Combined	Change
Albuquerque	897	450	−50%	0.1779	0.3686	108%
Atlanta	1035	530	−49%	0.2247	0.4110	83%
Boston	759	384	−49%	0.1419	0.2937	107%
Chicago	1081	569	−47%	0.1925	0.3702	92%
Cleveland	1150	512	−56%	0.1705	0.3765	121%
Fort Worth	920	433	−53%	0.1253	0.3228	157%
Houston	920	429	−53%	0.1714	0.3805	122%
Los Angeles	805	409	−49%	0.1822	0.3900	114%
Miami	736	304	−59%	0.1386	0.3300	138%
Salt Lake City	644	347	−46%	0.1692	0.3082	82%
Washington, DC	1081	650	−40%	0.1359	0.2820	108%

would benefit somewhat less than Cleveland Center would from using this algorithm. The relatively large benefits for Cleveland may be the result of the relatively large number of sectors in Cleveland Center, or of MAP values that are set relatively high in this Center. Operational sector combination data are required to determine actual benefits over current operations in each Center.

Figures 5 and 6 are histograms that show distribution of the average daily sector hour savings for the eleven Centers. These results indicate that all Centers would save at least 200 sector hours each day if the restricted algorithm were used rather than not combining any sectors, and some would save up to 500 sector hours. For example, by subtracting the average number of combined sector hours per day in Cleveland Center (642 sector hours) from the uncombined sector hours (1150 sector hours), the average daily

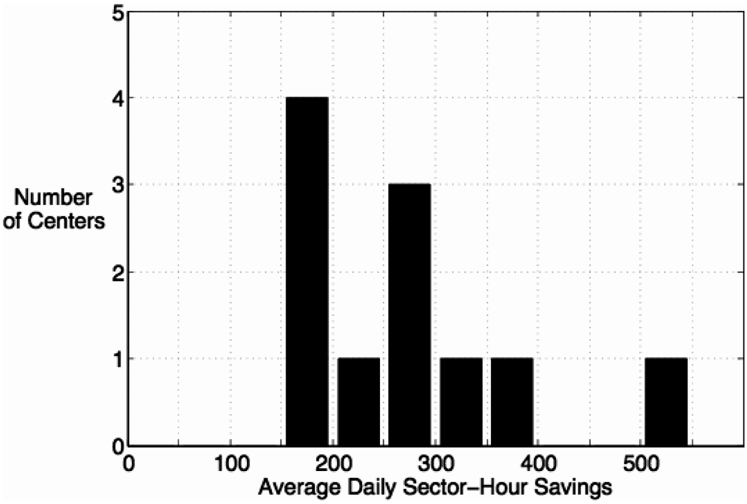

Figure 5. Histogram of average sector-hour savings per day in various Centers when the restricted algorithm is used.

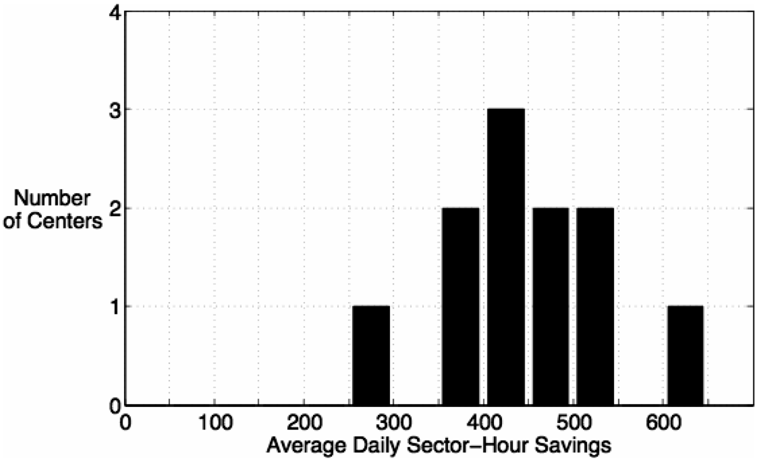

Figure 6. Histogram of average sector-hour savings per day in various Centers when the unrestricted algorithm is used.

sector-hour savings can be computed for Cleveland Center (508 sector hours). If the unrestricted algorithm were used, the savings range between 300 and 650 sector hours per day.

Parametric Analysis. A parametric analysis was performed to determine the sensitivity of the performance of the algorithm to changes in one of the algorithm parameters. The analysis was performed for Cleveland Center. The parameter g was varied from 0% to 30% of the MAP of the combined sector. The analysis was performed for both the restricted and unrestricted algorithm.

The results of this analysis are shown in Figure 7. When the capacity gap is set to zero, the sector combinations produced by the

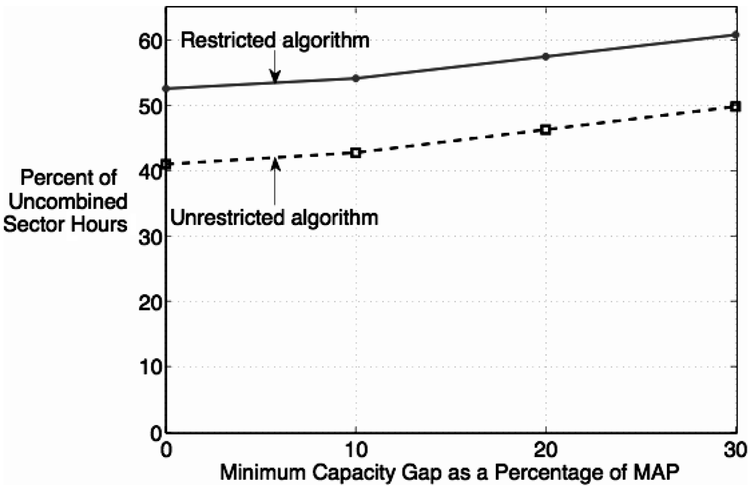

Figure 7. Effect of changes in g on sector hours required expressed as a percentage of uncombined sector hours.

unrestricted algorithm use only 40% of the sector hours that would be consumed by uncombined sectors over the course of the simulation. The restricted algorithm uses around 55% of the sector hours required by the uncombined sectors. As g increases, the sector hours requirement as a percentage of the uncombined sector hours increases to around 50% for the unrestricted algorithm and 60% for the restricted algorithm. Allowing more aggressive combinations leads to larger reductions in sector hours, but the sector-hour savings are relatively constant over the range of reasonable values for g.

Algorithm for Defining Groups of Sectors that May Combine. The algorithm for defining groups of sectors that may combine was run for Cleveland Center. The algorithm was trained on data from five of the seven dates mentioned previously and the resulting groups are specified in the Appendix. The algorithm defined eleven groups, each containing between three and six sectors. The current eight operational areas of specialization each contain seven or fewer sectors. It may seem that the operational areas of specialization would allow for more sector combinations because they contain more sectors, but the current areas contain both low and high sectors. Low and high sectors rarely combine, so the current eight areas of specialization are effectively sixteen groups of sectors that may combine. It is interesting to note that the algorithm-defined groups are significantly different from the existing areas. Some algorithm-defined groups contain sectors from up to four operational areas, and only one algorithm-defined group contains only sectors from the same operational area of specialization. The proposed and current sector groups may be significantly different because current areas of specialization contain both high and low sectors, while the proposed groups contain only one or the other. Another possible cause is that the new groups were proposed with the sole purpose of reducing sector hours, while existing areas were selected according to a broader set of criteria.

The resulting groups were tested by inputting them into the algorithm for combining sectors as the areas of specialization. The dates from February 2008, for which operational combinations are available, were used to test the performance of the algorithm. Table 5 contains some of the same information as Table 2 but shows the performance of the combining sectors algorithm when using the new groups. The new groups allow the combining sectors algorithm to reduce the number of sector hours an additional twenty sector hours per day for high sectors, bringing the total savings to 43% over uncombined sector hours for high sectors. These savings in sector hours are much larger than the savings of less than 30% achieved by operational combinations. An even greater increase in efficiency was achieved by the new groups in low sectors. While the combining sectors algorithm reduced the number of sector hours by 52% over uncombined sectors when using the existing areas, it was able to reduce the number of sector hours by more than 60% when using the new groups.

SUBJECT MATTER EXPERT FEEDBACK

Feedback regarding these algorithms was obtained during a visit to Cleveland ARTCC and personal communication with FAA operations managers and area supervisors. Some results from and lessons learned in these meetings and communication are discussed in this section.

Current Operations

Benefits of Combining and Splitting Sectors. The combining and splitting of airspace sectors is an important tool used at ARTCCs

Table 5. Performance of Algorithm for Defining New Groups of Sectors that May Combine

		High Sectors	Low Sectors
Uncombined	Sector Hours	621	529
Current Operations	Sector Hours	435	Not available
	% Change	–30%	Not available
Restricted Algorithm with Existing Areas	Sector Hours	376	256
	% Change	–39%	–52%
Restricted Algorithm with New Groups	Sector Hours	356	209
	% Change	–43%	–60%

to manage airspace and staff effectively. There are benefits to both combining sectors and to splitting sectors, so tradeoffs must be made when making these decisions.

Combining sectors frees up controllers to go to meetings, breaks, and briefings, and reduces the staff required to manage a piece of airspace. If a sector is not busy, it may be difficult for a controller to stay focused. Therefore, combining sectors can increase controller productivity even while leading to busier sectors. Moreover, combined sectors are more likely to require two controllers than separate sectors, and the benefit of having two controllers working a sector generally exceeds the additional difficulty of controlling more traffic. Finally, combined sectors lead to fewer airspace-induced flight restrictions. For example, controllers can give more direct routings when working aircraft in larger combined sectors.

Combined sectors are primarily split to reduce the workload in the sectors and thereby increase safety. The reduced workload that results from splitting a sector may enable controllers to find more efficient resolutions to conflicts. Moreover, controlling fewer aircraft leaves controllers with more time to provide higher quality service to aircraft. Higher quality service can include direct routings, the provision of weather information, or altitude changes to reduce turbulence.

Operations for Combining and Splitting Sectors. Area supervisors currently make the decisions to combine or split sectors based upon their experience and judgment. There are many considerations when making this decision, such as sector workload, expected future sector workload, number of staff available, the training/certification level of each available staff member, airport configurations, weather, and radio frequency coverage. The two-dimensional shape (i.e. convexity) of the resulting sectors is usually not a concern when combining or splitting sectors. However, combined sectors should not contain too many altitude steps (discussed previously). Sectors also cannot be combined or split too frequently, and the controllers must have enough time to prepare for the combination or splitting. Currently, sectors are combined or split as frequently as every half an hour and with as little lead time as a few minutes.

When sectors are split, the main operational cost is a briefing in which the controller working the combined sector explains the status of the sector. At the time of the briefing, the controller is typically busy controlling the sector, so doing a briefing at the same time is difficult. Aside from the risk involved with a busy controller simultaneously doing a briefing, there is an additional risk that some important information about the portion of the sector to be split off might be communicated poorly or not communicated at all. These issues suggest that the splitting of sectors should be executed prior to the time when they are so busy that splitting is required. Moreover, these operational costs of splitting sectors imply that sector combinations should only be executed when the expected benefit is sufficiently large and when the combination is expected to be in place for a sufficiently long time.

The operational cost of combining sectors is usually smaller than that of splitting sectors. By the time sectors are combined, they are not busy. This suggests that sector combination decisions could be made sooner than they are currently.

Feedback on Algorithms

Almost all of the FAA participants responded positively to the algorithm for combining sectors. In particular, a tool based on this algorithm would be immediately useful for area supervisors as they make decisions about how to combine or split airspace sectors. The algorithm does not take into account every factor that is considered when deciding to combine or split sectors, but the suggested sector combinations would augment the supervisors' judgment and give them more confidence in their decisions. While many area supervisors are experienced enough to make excellent decisions about combining sectors, the tool would be especially helpful for newer or substitute supervisors or for unusual traffic situations.

Of even more interest to the FAA participants was the algorithm for determining groups of sectors that may combine. At the time of the visit, this algorithm was not complete. However, the participants were eager to see results of an earlier algorithm that suggested sectors to be "shared" between two areas. The process of defining controller areas of specialization is currently done through negotiations between area representatives (supervisors and controllers), without the help of quantitative data or a systematic approach, and the results are often controversial. The algorithm for defining groups of sectors that may combine would help meet a felt need of the FAA participants.

The FAA participants also suggested several additional features or modifications to the algorithms. A better measure of sector utilization than aircraft count and a better measure of capacity than MAP should be used, such as dynamic density. The algorithms could be augmented to consider staffing factors, such as staff certification constraints and the objective of ensuring that available controllers are given enough time controlling sectors. Equipment issues also play a role in sector combination decisions, and the algorithms could explicitly consider these issues. For example, if two large sectors are combined, the resulting sector may be too large to be displayed on a scope at a resolution that allows controllers to vector aircraft into final approach to airports in the sector. Similarly, radio frequency coverage may prevent some sector combinations. Furthermore, the repeatability of sector combinations must be considered for controller situational awareness and for staff planning purposes. First of all, controllers must be familiar with the sector combinations that they are asked to control. Secondly, the number of sector changes that occur at any one time must not be too dramatic. Finally, repeatability in the number of open sectors at various times would enable more efficient staff scheduling. When these issues are either explicitly considered by the algorithm or when area supervisors augment the algorithm-suggested sector combinations to consider these issues, the performance of the algorithm, as measured by sector hours, may change.

The current algorithms do not consider these and other factors, so there was some concern that area supervisors would make poor sector configuration decisions by using the output of the algorithm. However, some participants were confident that area supervisors would utilize the output of the algorithm along with other factors to make improved sector configuration decisions.

FUTURE RESEARCH

Several areas of future research have been identified. The algorithms could use dynamic density to measure the sector workload more accurately. Staffing constraints could be added to the algorithms. Finally, the output of these algorithms should be analyzed to determine if the resulting sector combinations are sufficiently repeatable for controller situational awareness to be maintained and to enable efficient staff scheduling. This will be done by comparing the repeatability of operational sector combinations with the repeatability of the combinations proposed by this algorithm. The algorithms may have to be augmented if their output is not sufficiently repeatable.

Hopefully, this research will progress towards the development of operational procedures, human-in-the-loop experiments, and field tests. Such research is needed to ensure that the algorithm would perform safely and efficiently if it were deployed. Feedback from subject matter experts and air traffic management practitioners will be pursued as this research is conducted. The algorithms will be refined based on feedback from these experts and the results of this research.

CONCLUSION

Two algorithms have been proposed for reducing the air traffic control resources required to manage a region of airspace. The first is a heuristic for combining airspace sectors. Operational sector combinations of high altitude sectors at Cleveland Center reduce the number of required high altitude sector hours by nearly 30% over uncombined sector hours. The restricted combining sectors algorithm can reduce the required high altitude sector hours by almost 40%, and the unrestricted version of the algorithm achieves a reduction of more than 47%. Results are even more significant for low altitude sectors: the restricted algorithm can reduce the required sector hours by more than 50% over the uncombined low sectors. Simulations of actual traffic data from 11 Centers demonstrate that the use of this algorithm reduces the total number of sector hours required to manage a Center's airspace by between 20% and 45% over the number required when no sectors are combined. The unrestricted algorithm can reduce the total number of sector hours by between 40% and 60%. The utilization of the deployed sectors is also higher when the algorithm combines sectors.

A second heuristic algorithm for defining groups of sectors that may combine was also proposed. When the first algorithm uses the groups suggested by this algorithm as a new set of areas of specialization, the number of sector hours required to manage Cleveland Center is reduced by 43% and more than 60% over the number required when no sectors are combined for high and low altitude sectors, respectively. Feedback on these algorithms and results from FAA employees at Cleveland Center indicate that both of these algorithms would be immediately useful in ARTCCs.

ACKNOWLEDGEMENTS

The authors are grateful to Mark Evans, a consultant to NASA, for his detailed comments and suggestions and for interfacing with Cleveland ARTCC. Also, the authors would like to thank Ron Wood (Support Manager for Airspace and Procedures, Cleveland ARTCC), John Aston (Supervisory Traffic Management Coordinator, Cleveland ARTCC), Al Mahilo (Supervisory Traffic Management Coordinator, Cleveland ARTCC), Bill Hikade (Operations Supervisor, Area 5, Cleveland ARTCC), Mark Madden (Manager, System Operations, Cleveland ARTCC), Tom Roherty (Strategic Customer Advocate, Cleveland ARTCC), Bill Nunn (Operations Supervisor, Area 5, Cleveland ARTCC), and Lowell Hought (Operations Manager, Minneapolis ARTCC) for their feedback, questions, and suggestions regarding this work.

ACRONYMS

ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ASDI	Aircraft Situational Display to Industry
DAC	Dynamic Airspace Configuration
ETMS	Enhanced Traffic Management Tool

FAA	Federal Aviation Administration
FACET	Future ATM Concepts Evaluation Tool
MAP	Monitor Alert Parameter
NAS	National Airspace System

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APPENDIX: NEW GROUPS OF SECTORS THAT MAY COMBINE IN CLEVELAND CENTER

Table A.1 shows the groups suggested by the algorithm for finding new groups of sectors that may combine. The current area of the sectors can be determined by investigating the first digit in the two-digit sector number. Sectors in the same area have the same first digit.

Table A.1. New Groups of Sectors that May Combine in Cleveland Center Suggested by Algorithm

New Group Number	Type	Number of Sectors	Sectors	Number of Existing Areas
1	High	6	19, 29, 26, 38, 46, 47	4
2	Low	6	04, 03, 50, 75, 05, 40	4
3	Low	5	55, 53, 06, 52, 61	3
4	High	6	36, 39, 79, 74, 37, 77	2
5	Low	3	15, 01, 02	2
6	High	4	64, 45, 65, 49	2
7	Low	4	16, 14, 12, 21	2
8	High	3	48, 57, 59	3
9	High	4	07, 28, 27, 18	3
10	Low	5	33, 70, 20, 31, 73	3
11	High	4	67, 68, 69, 66	1

There are currently eight areas of specialization in Cleveland Center. Each contains both low and high sectors, so there are currently sixteen groups of sectors that may combine in Cleveland Center. These eleven new groups of sectors that may combine could be used as building blocks for defining new controller areas of specialization in Cleveland Center. Physical equipment and facility constraints in Cleveland Center permit at most eight areas of specialization, each with at most eight sectors. Pairs of these new groups with a total of eight or fewer sectors could be merged together to build a new area. The process of using these groups to define new areas would likely involve area representatives (controllers and area supervisors).

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